Axion & vector **dark matter** search with **GW detectors**

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Based on Nagano, TF, Obata & Michimura PRL123,111301(2019)
Michimura, TF, Morisaki, Nakatsuka & Obata PRD102, 102001(2020)
Morisaki, TF, Michimura, Nakatsuka & Obata [arXiv:2011.03589]

@ 7th KAGRA International Workshop on 19th Dec. 2020

Message

GW detectors search for dark matter

- aLIGO O1 data ⟶ $\times 10$ better bound on Vector DM
- Ongoing KAGRA projects probing Axion DM & Vector DM
- Huge parameter space will be searched by future GW detectors

Maybe we'll discover DM with GW interferometers!!

Outline

Introduction to dark matter search

- General ideas
- Axion DM & Vector DM

GW detectors probing dark matter

- KAGRA search for Axion DM
- aLIGO's sensitivity to Vector DM
- KAGRA search for Vector DM

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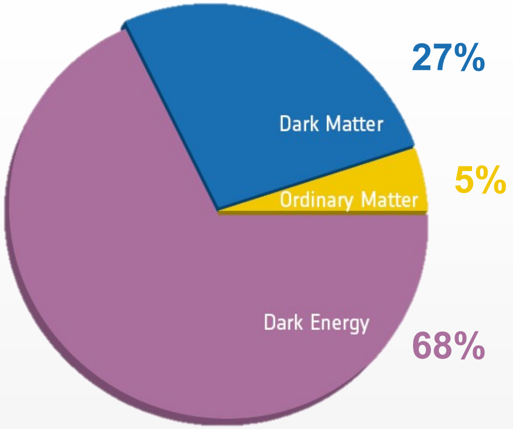
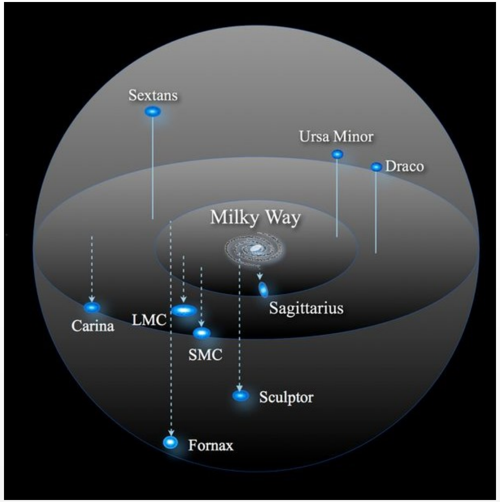
Dark Matter

Cosmic pie chart

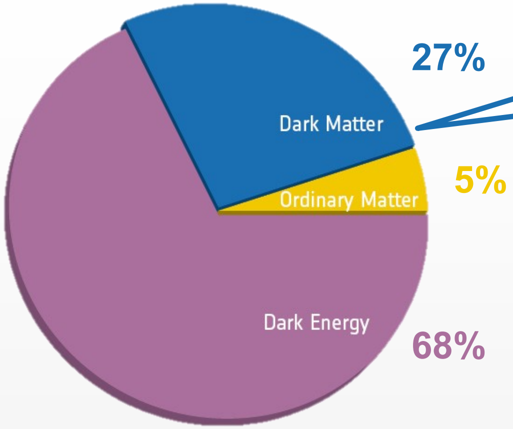


Local DM Halo



Dark Matter

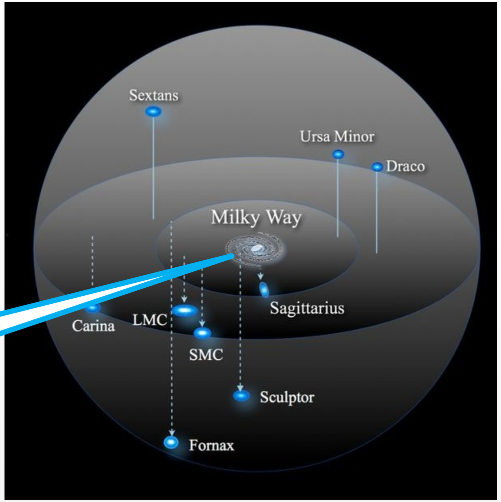
Cosmic pie chart



$\bar{\rho}_{\rm DM} \approx 10^{-6} {\rm GeV/cm^3}$

$\rho_{\rm DM}^{\rm local} = 0.3 {\rm GeV/cm^3}$

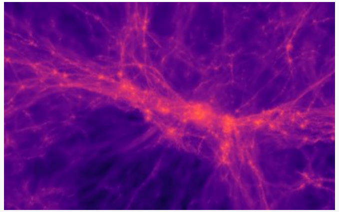
Local DM Halo



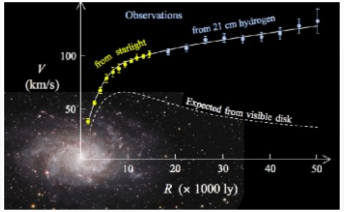
We live inside a high density DM halo!

DM Search I

Existence of DM is confirmed
only through its gravitational interaction



Structure formation



Galaxy rotation curve

Gravitational lensing

Bullet cluster

→ **DM is something gravitating**

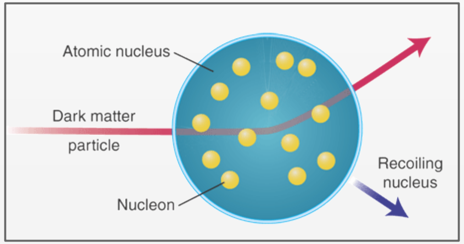
DM Search II

Unsatisfied… → **We want to identify DM!**

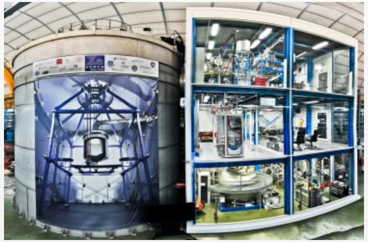
1. Assume a DM model with **additional interaction**

2. Search for its signal

WIMP case

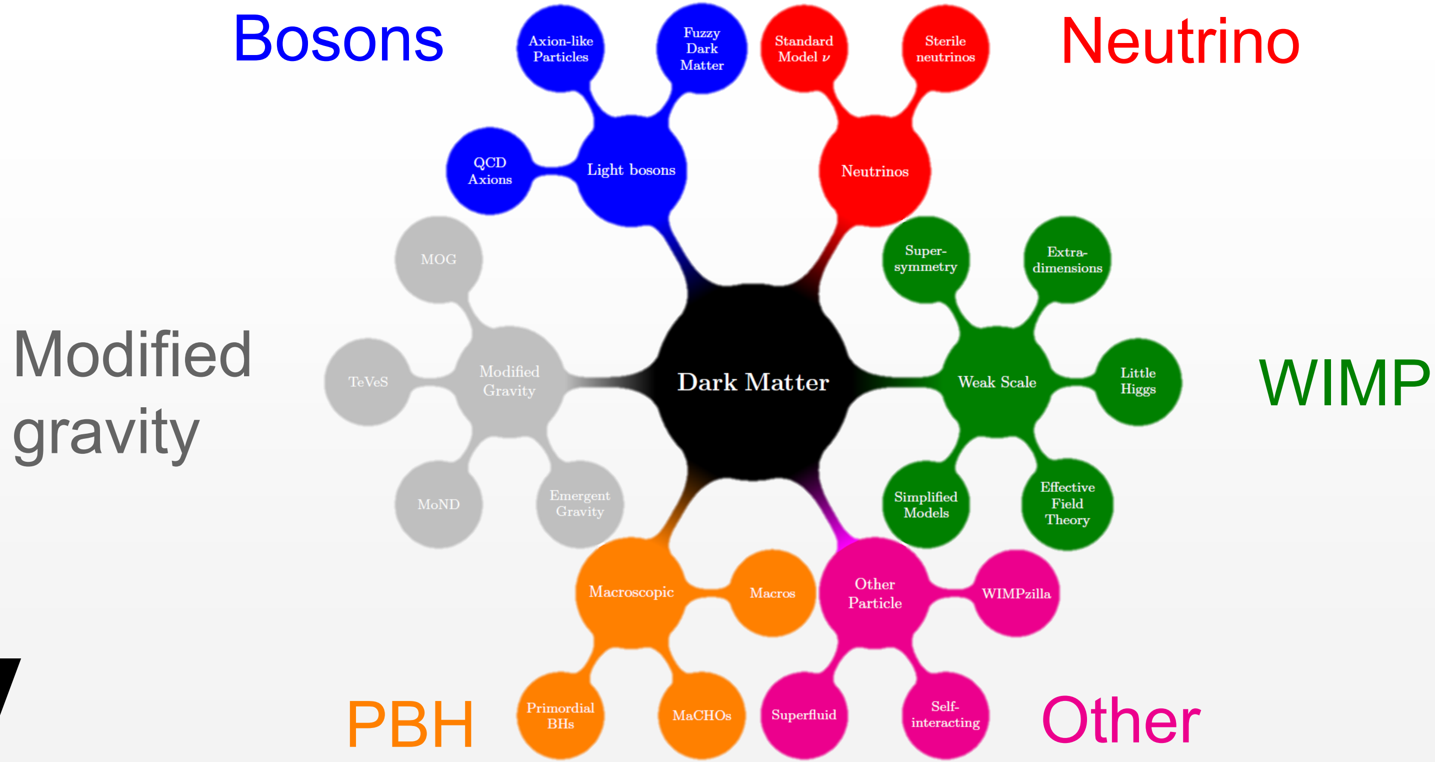


WIMP scatters with nuclei

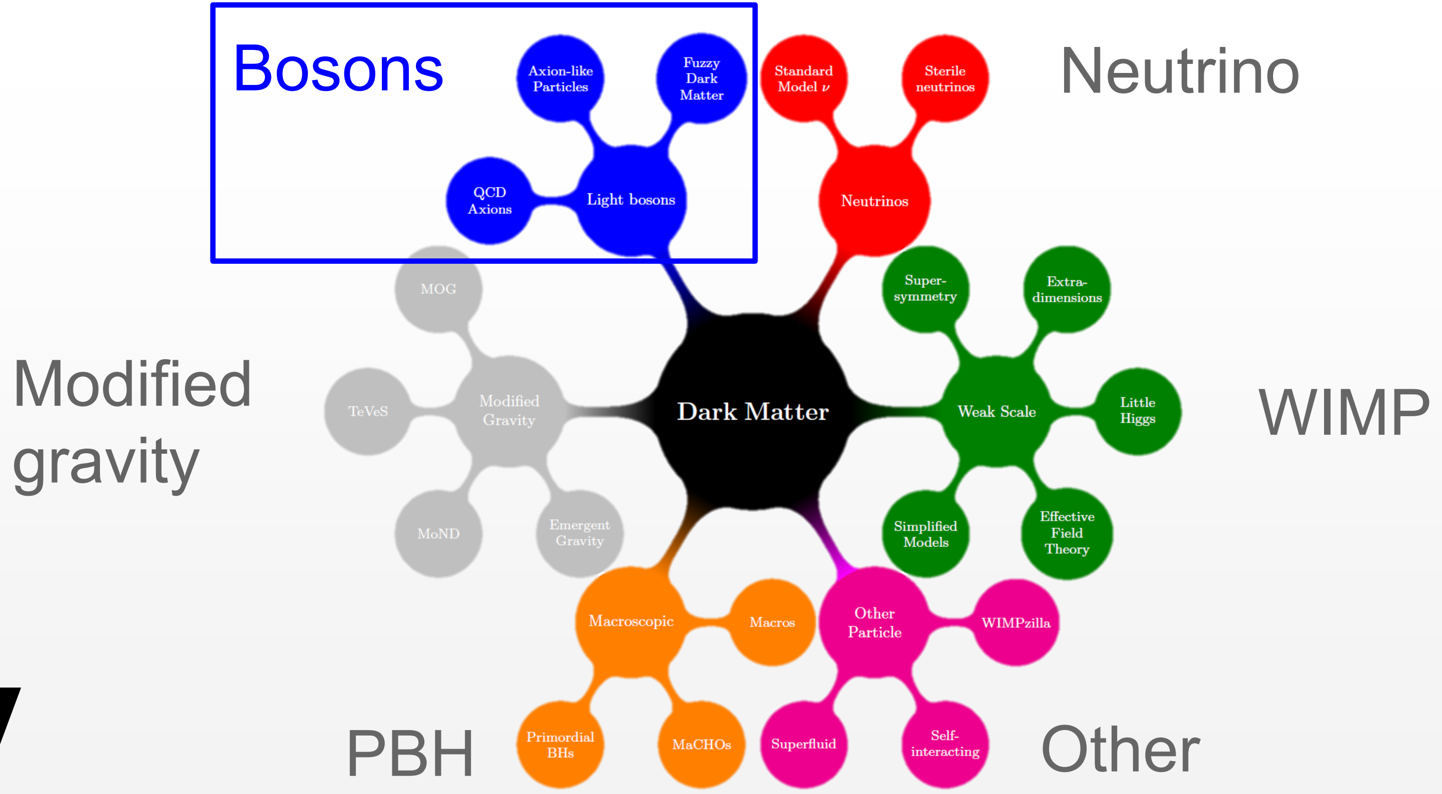


Underground experiment
(Xenon 1T)

DM Candidates



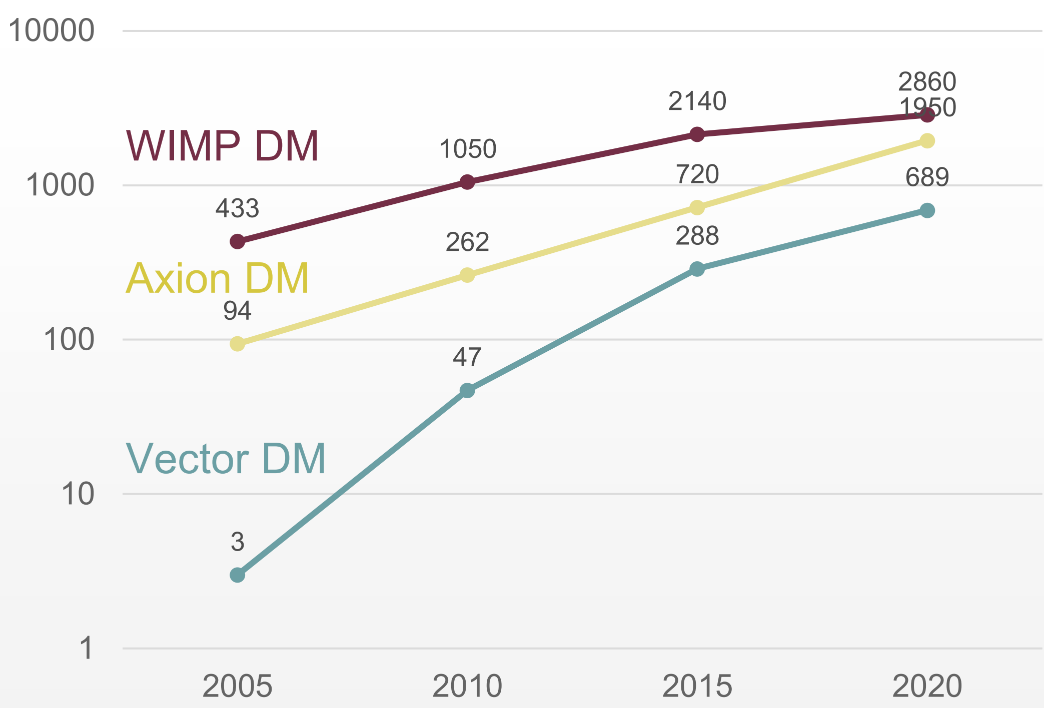
DM Candidates



Who's popular?

of paper

The hit count of
"XX dark matter"
in Google scholar
for every 5 years



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- KAGRA search for Vector DM

Vector DM (a.k.a. Dark photon DM)

VDM = Electric wave with a mass

Theory : $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$

Electromagnetism with a mass

Electric part : $\boldsymbol{E} = -\dot{\boldsymbol{A}} \sim \omega \boldsymbol{A},$

Magnetic part : $\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A} \sim k\boldsymbol{A},$

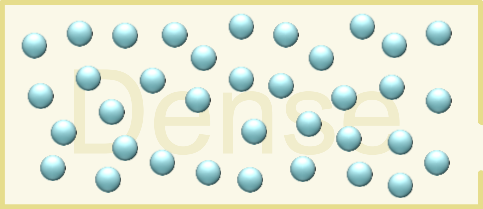
Dispersion relation : $\omega^2 = k^2 + m_A^2 \simeq m_A^2 \gg k^2,$ $\left(k = m_A v, \quad v_{\rm DM}^{\rm local} \approx 10^{-3} c\right)$

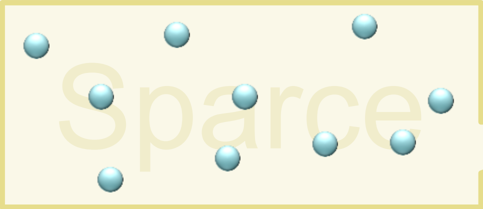
$\Rightarrow$ $\boldsymbol{E} \simeq \boldsymbol{E}_0 \cos(m_A t) \gg \boldsymbol{B}$

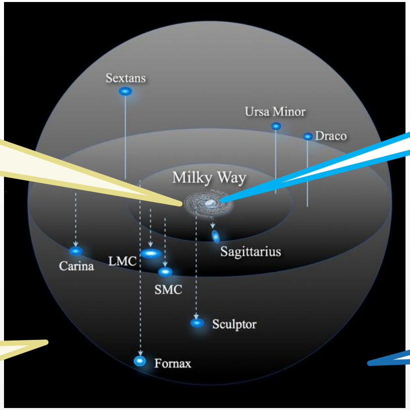
Electr~~omagnet~~ic wave!

DM density

WIMP





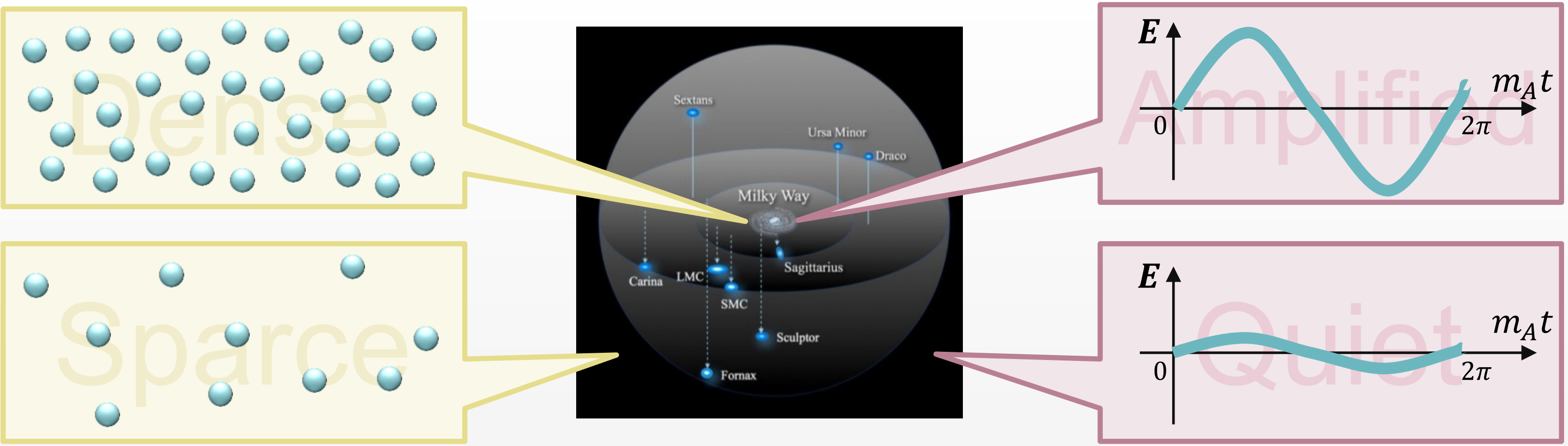


$$\rho_{\mathrm{DM}}^{\mathrm{local}} = 0.3\mathrm{GeV/cm^3}$$

$$\bar{\rho}_{\mathrm{DM}} \approx 10^{-6}\mathrm{GeV/cm^3}$$

DM density

WIMP | **Vector DM**

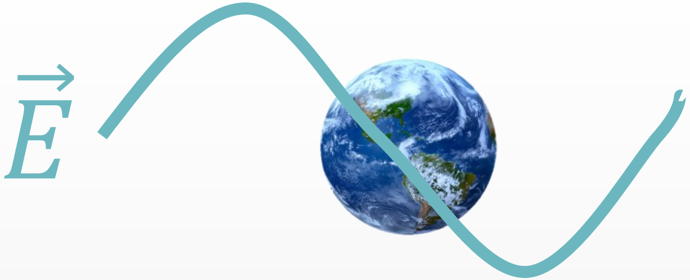


Wave-like DM is also a good candidate!

VDM syndrome? (spoiler: Joke slide)

Swiss people protest 5G

Any health problems by Vector DM?



Don’t worry ☻

VDM coupling to normal matter is very much suppressed.

VDM Coupling

VDM = Electric wave with a mass

Theory : $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$ $(D = B \text{ or } B-L)$

Additional Interaction

Charge for VDM = B (baryon #) or B-L (baryon # - Lepton #)

[Note: B(proton)=B(neutron)=L(electron)=1, otherwise=0]

Coupling strength relative to electromagnetism : $\epsilon_B, \epsilon_{B-L} \lesssim 10^{-23}$

→ **Need to be extremely sensitive!**

Axion DM (a.k.a. ALP DM)

Similar to VDM. Wave-like DM $\phi = \phi_0 \cos(m_\phi t)$

But, 3 differences. ADM is

1. Scalar : no direction
2. Parity violating : Left & right become asymmetric
3. Coupled to photons : $\mathcal{L}_{\text{int}} = \frac{1}{4} g \phi F^{\mu\nu} \tilde{F}_{\mu\nu}$ (Chern-Simons coupling)

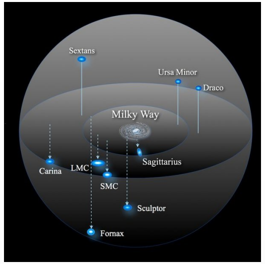
⇒ **ADM = Birefringent media**

Photon in ADM

EoM for photon with ADM ϕ is

$$[\partial_t^2 - \nabla^2]\boldsymbol{A} = \underline{-g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}} \quad \Leftarrow \quad \phi = \phi_0 \cos(m_\phi t)$$

Additional Interaction



live in ADM

Dispersion relations of left/right polarization are modified as

$$\omega_{L,R}^2 = k^2\left[1 \pm g\phi_0 \frac{m}{k}\sin(mt)\right] \qquad (i\hat{\boldsymbol{k}} \times \boldsymbol{e}_{L,R} = \pm\,\boldsymbol{e}_{L,R})$$

Speed of light changes depending on circular polarization!

→ **ADM = Birefringent media**

DM Summary

	Vector	Axion	WIMP
Image	**Electric wave with a mass**	**Birefringent media**	**Massive Particle**
Interaction	**B** or **B-L**	**Photon**	**Nuclei**
Search	**?**	**?**	**Particle collider** **Undergrond exp.**

N.b. other interactions are also possible

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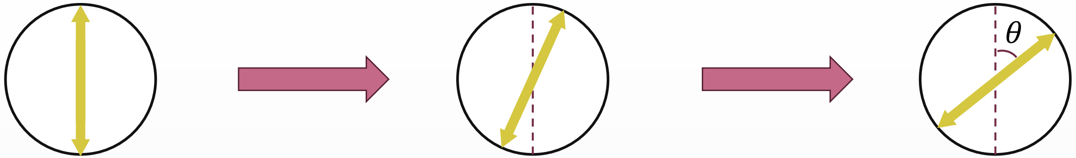
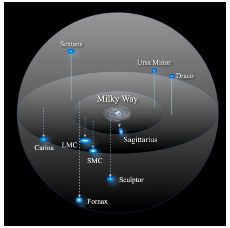
Optical Rotation by ADM

Linearly polarized photons traveling in ADM rotates its pol. plane





live in ADM

Rotation angle θ for light path L is

$(\rho_{\rm DM}^{\rm local} = m_\phi^2 \phi_0^2/2 \approx 0.3 {\rm GeV/cm^3})$

$$\theta \simeq g\phi_0 \sin(mL/2) \xrightarrow{mL \ll 1} 10^{-14} \left(\frac{g}{10^{-12}{\rm GeV}^{-1}}\right)\left(\frac{L}{3{\rm km}}\right)$$

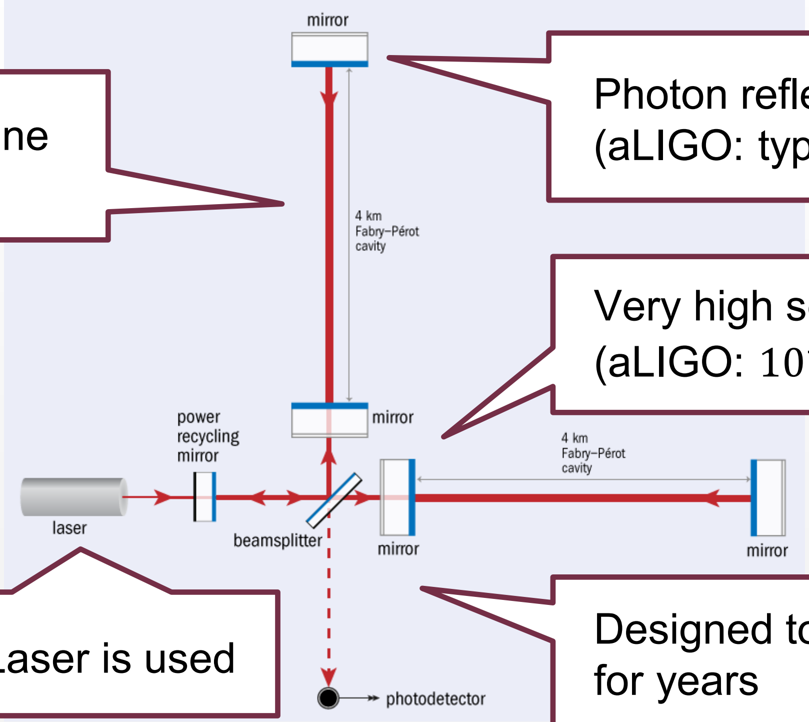
Signal is small! So we need

1 **Long light path** 2 **High sensitivity** 3 **Long runtime**

GW interferometer is ideal!!

Very Long Baseline
(aLIGO: 4km)

Photon reflects many times
(aLIGO: typically 500 times)



Very high sensitivity
(aLIGO: $10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$)

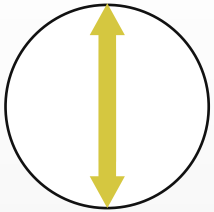
Linear Polarized Laser is used

Designed to run
for years

Measure ADM signal

Nagano, TF, Obata & Michimura
PRL123,111301(2019)

Measure the **s-polarized light** induced by ADM birefringence



Originally
P-polarized

Measure ADM signal

Nagano, TF, Obata & Michimura
PRL123,111301(2019)

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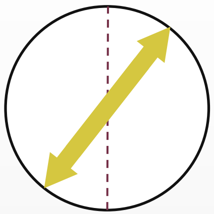

Optical
rotation

Measure ADM signal

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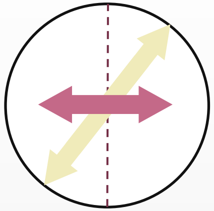

S-polarization
produced by
ADM

Measure ADM signal

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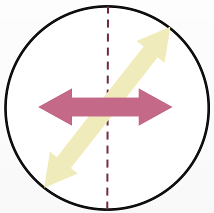
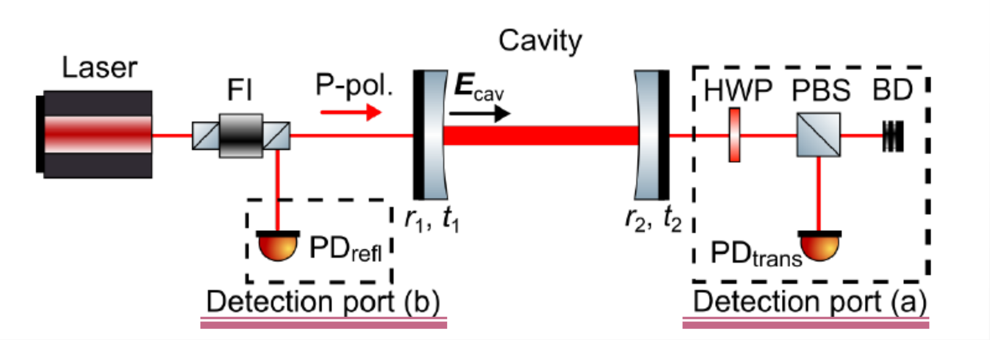


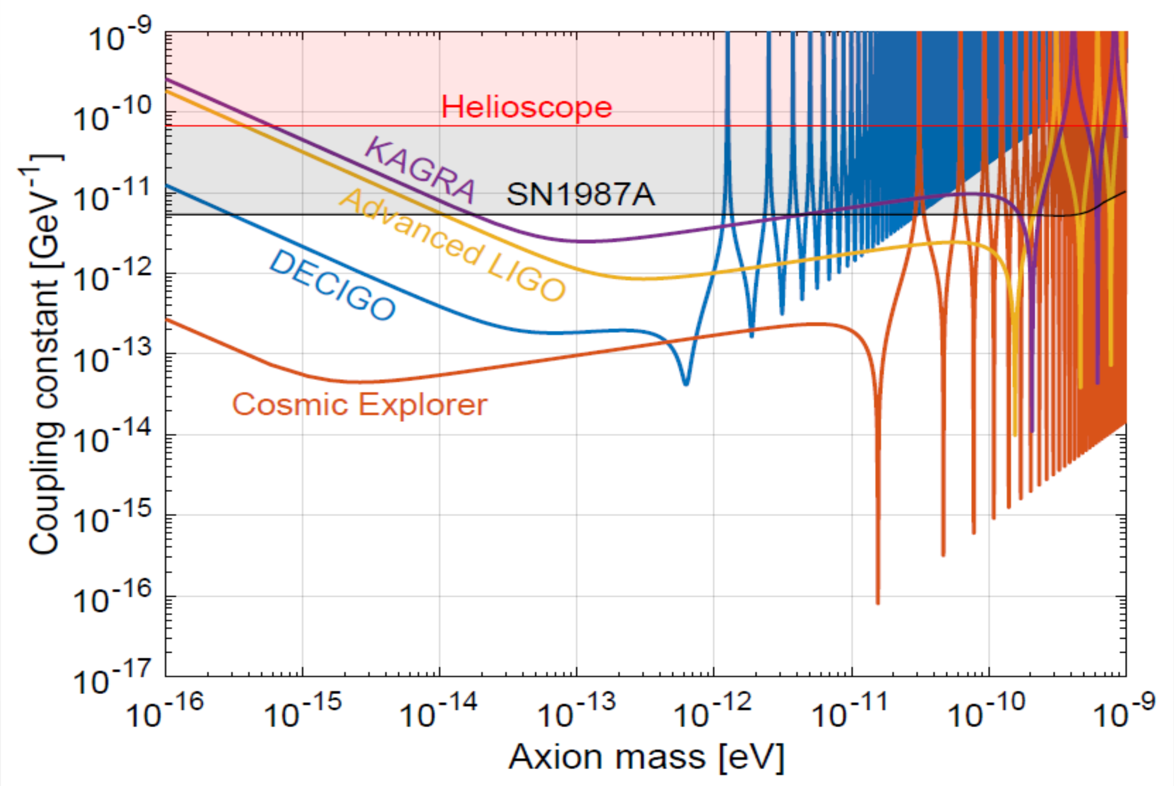
S-polarization produced by ADM



Adding a photodetector at port (a) or (b) makes KAGRA an ADM detector.

This ADM search is compatible with GW observation

Sensitivity to ADM for 1 year run



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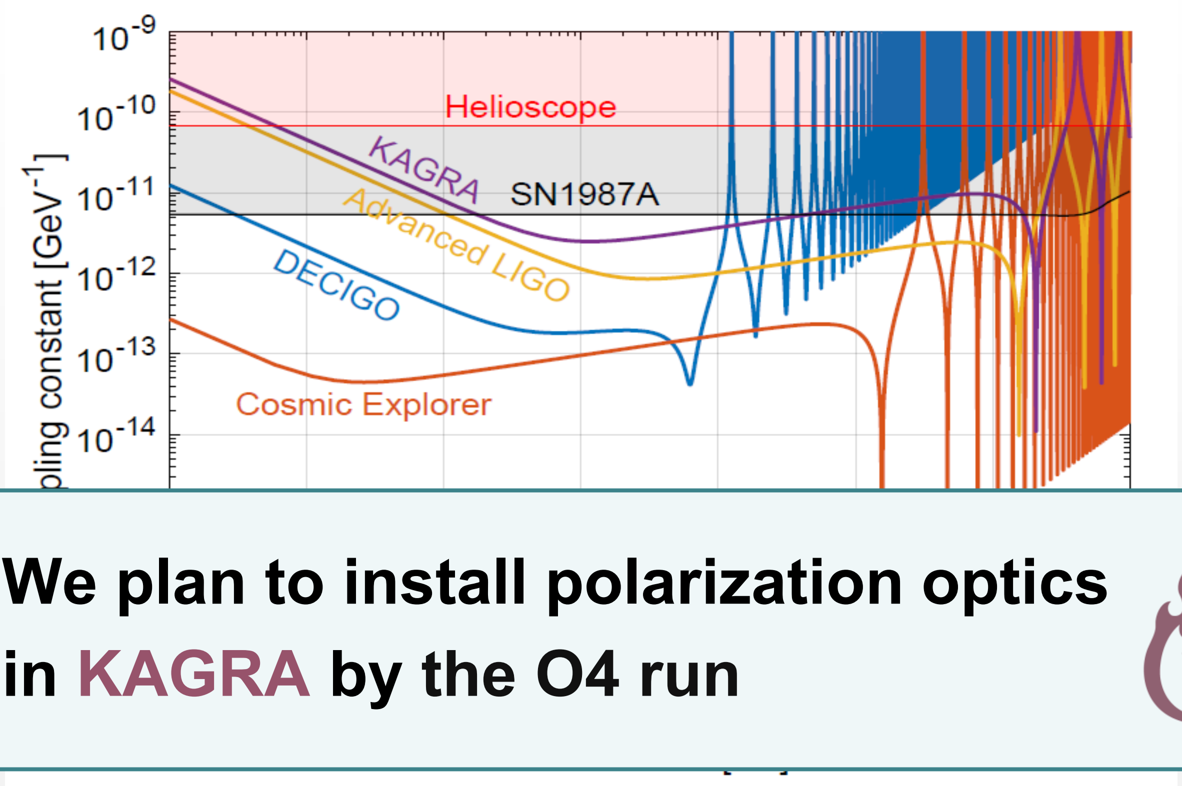

We plan to install polarization optics in KAGRA by the O4 run

KAGRA
will be the
world’s best
ADM detector!

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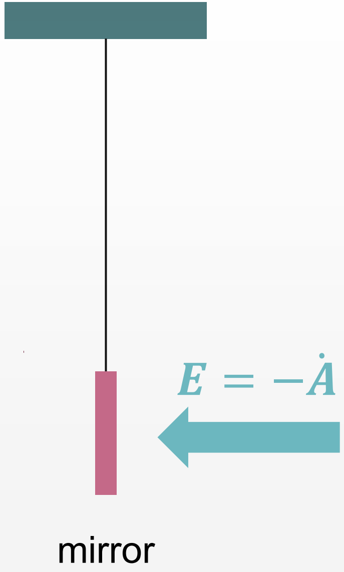
VDM acts on Mirrors

VDM (≈ electric wave) pushes mirrors, just as $\vec{E}$ does electrons.

VDM : $\boldsymbol{A} = \boldsymbol{A_0} \sin[m_A(t - \boldsymbol{v} \cdot \boldsymbol{x})]$

Force : $\boldsymbol{F} = -\epsilon_D e Q_D \dot{\boldsymbol{A}}$

Mirror : $\delta \boldsymbol{x} = \dfrac{\epsilon_D e Q_D}{m_A M} \boldsymbol{A_0} \sin[m_A t]$



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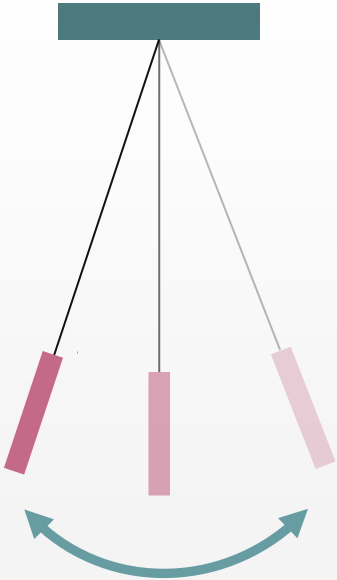


VDM oscillates mirrors

Common Motion

Pierce, Riles and Zhao, PRL121, 061102 (2018)

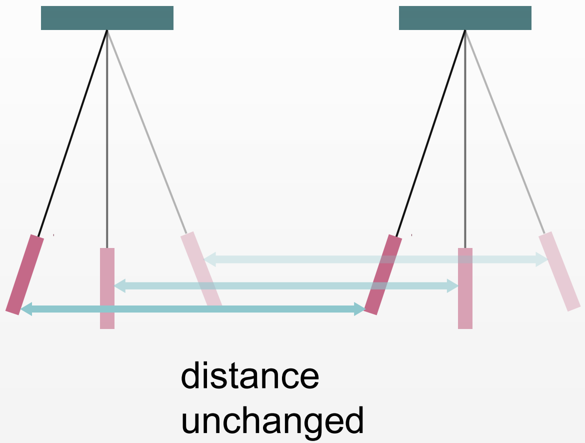
GW detectors measure the differential motion of the mirrors

Wavelength of VDM is

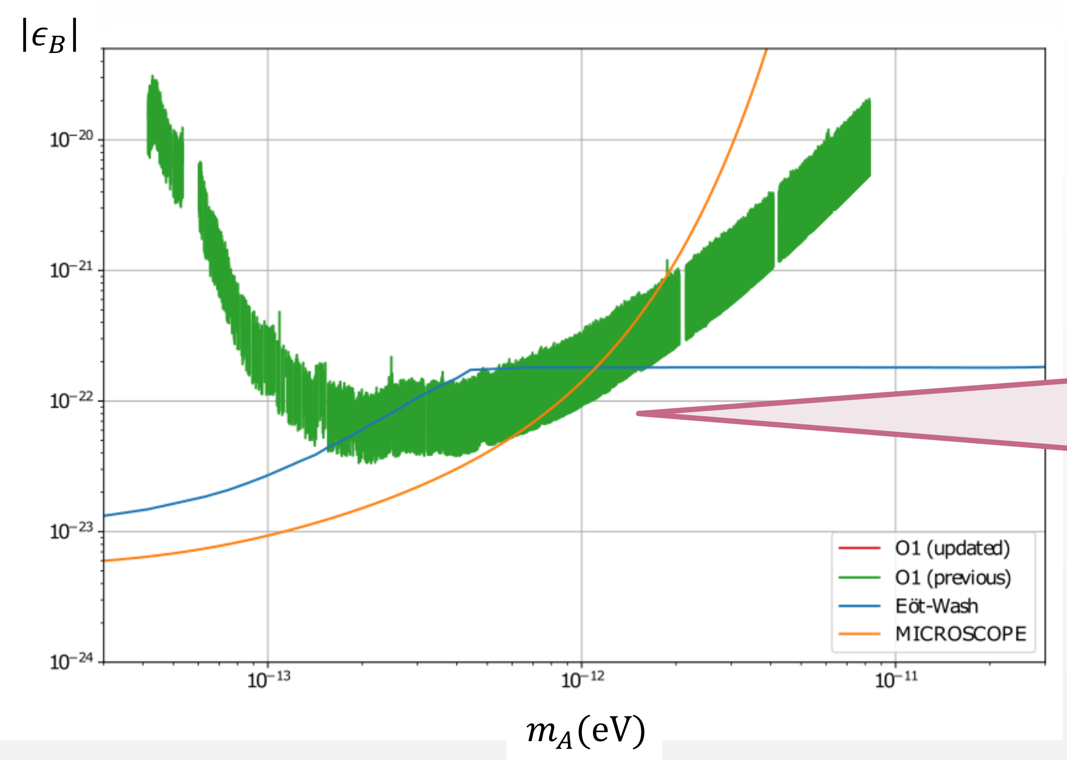
$$\lambda_{\mathrm{VDM}} = \frac{2\pi}{m_A v_{\mathrm{DM}}} \simeq 10^7 \mathrm{km} \left(\frac{m_A}{10^{-13}\mathrm{eV}}\right)^{-1} \gg L_{\mathrm{arm}}$$

VDM looks like homogeneous $\boldsymbol{E}$

➡ Signal suppressed by $(m_A v_{\mathrm{DM}} L_{\mathrm{arm}})$



Previous bound on VDM coupling to B from aLIGO O1 data



Pierce, Riles and Zhao, PRL121, 061102 (2018)

Guo, Riles, Yang and Zhao, Commun.Phys.2, 155 (2019)

Morisaki, TF, Michimura, Nakatsuka and Obata [arXiv:2011.03589]

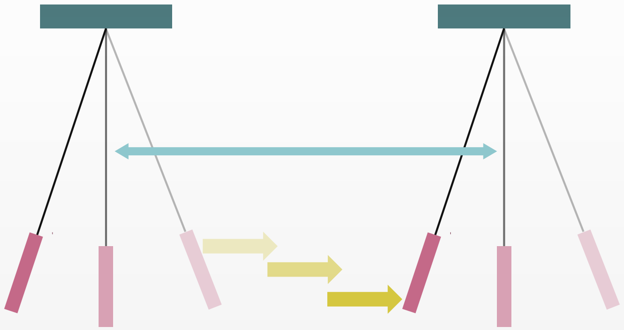
comparable to the other constraints by EP test

$c \neq \infty$ Effect

Morisaki, TF, Michimura, Nakatsuka and Obata [arXiv:2011.03589]

There exists a VDM signal even if the mirror motion is common.

“Finite light-traveling time effect”



If round-trip time = period of VDM

$(L_{\mathrm{arm}}/c = \pi/m_A)$

$c \neq \infty$ Effect

Morisaki, TF, Michimura, Nakatsuka and Obata [arXiv:2011.03589]

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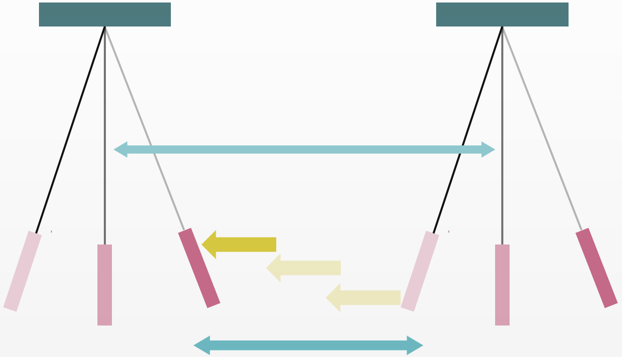

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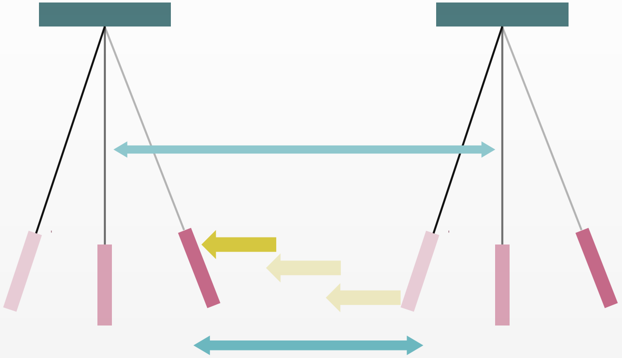
“Finite light-traveling time effect”

$$c\tau_{\mathrm{VDM}} = \frac{2\pi c}{m_A} \simeq 10^4\mathrm{km}\left(\frac{m_A}{10^{-13}\mathrm{eV}}\right)^{-1} \gg L_{\mathrm{arm}}$$

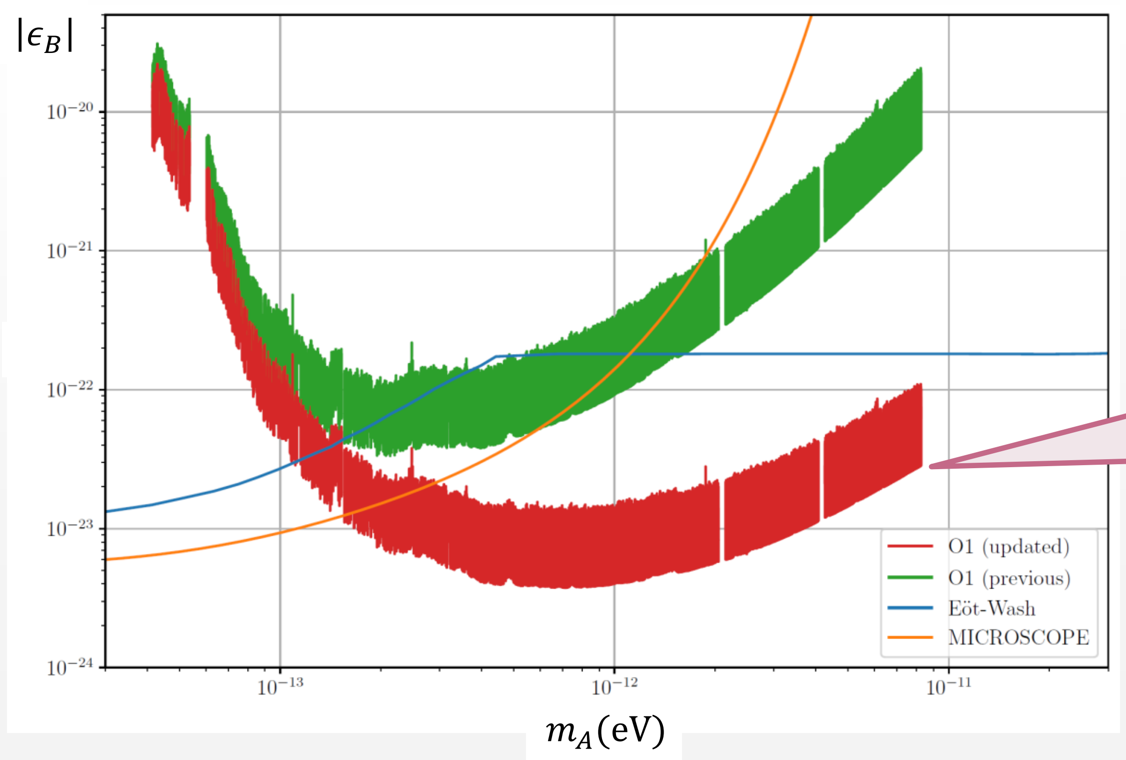
Signal suppressed by $(m_A L_{\mathrm{arm}})^2$

But still, it yields the dominant signal



Actual bound is better!

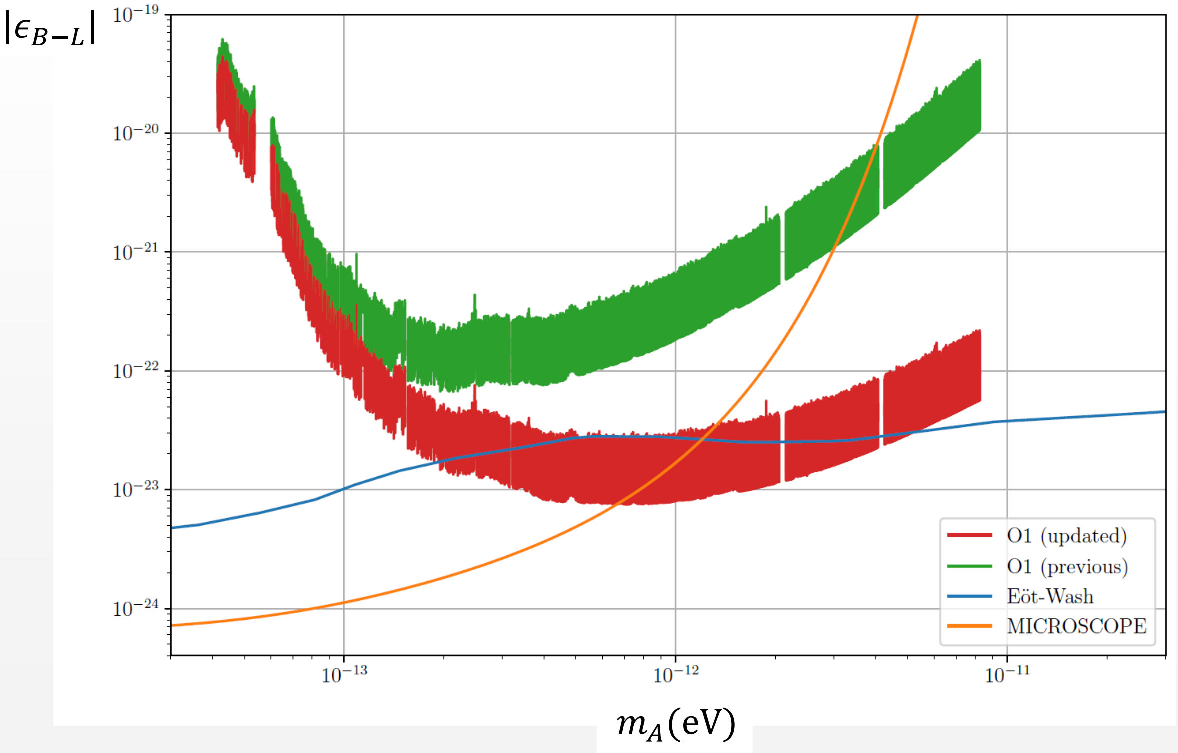
Updated bound on VDM coupling to B from aLIGO O1 data



Morisaki, TF, Michimura, Nakatsuka and Obata [arXiv:2011.03589]

×10 improved the constraint

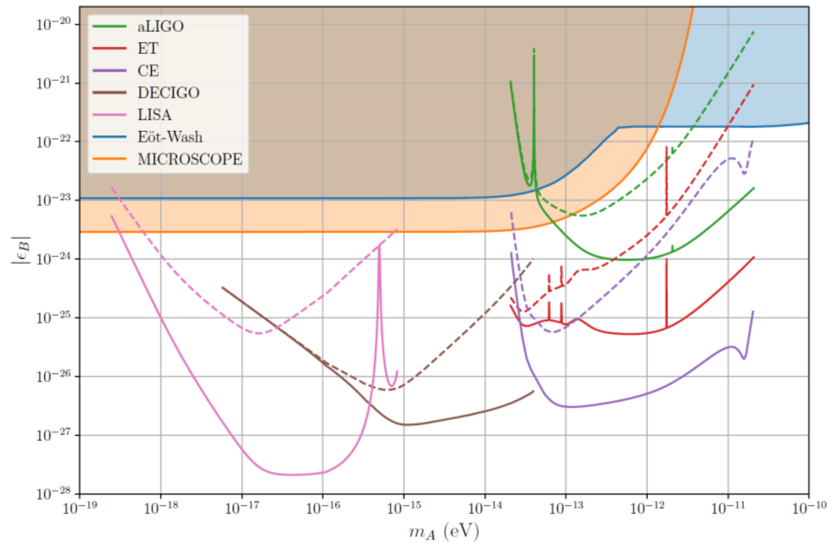
Updated bound on VDM coupling to B-L from aLIGO O1 data

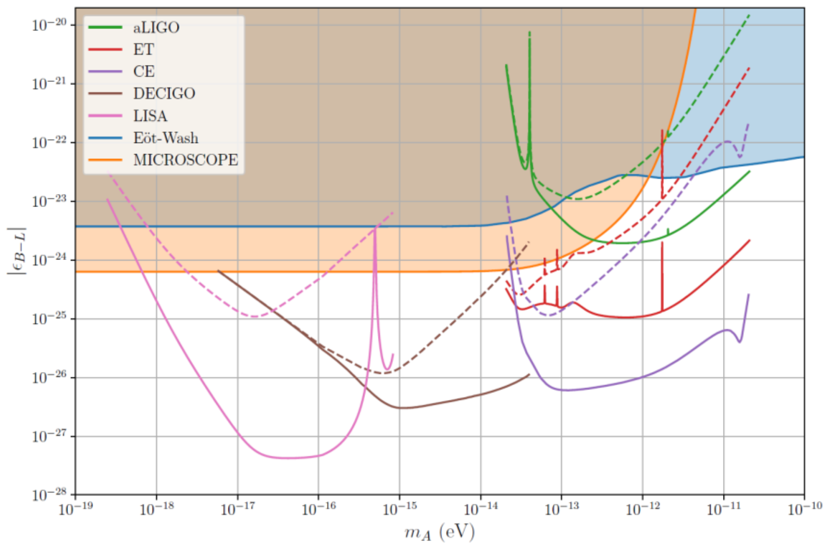


Morisaki, TF, Michimura, Nakatsuka and Obata [arXiv:2011.03589]

Morisaki, TF, Michimura, Nakatsuka and Obata [arXiv:2011.03589]

Projected sensitivity of future GW detectors





Promising improvement by upcoming experiments without design change.

LISA, DECIGO,…

may discover dark matter!

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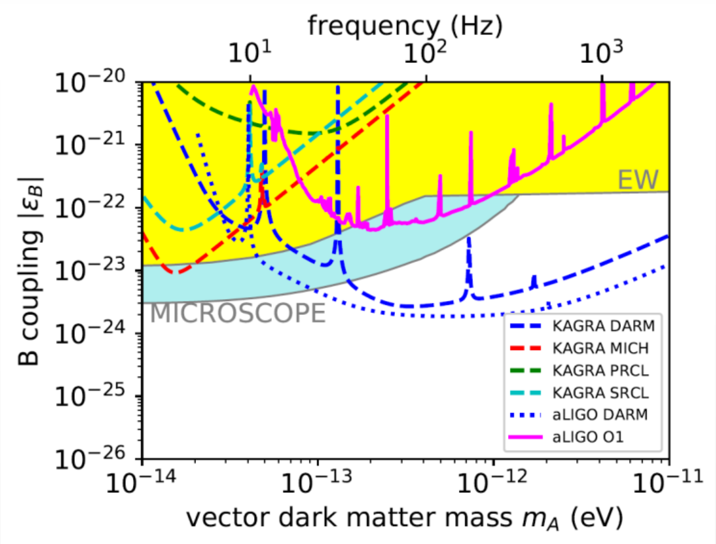
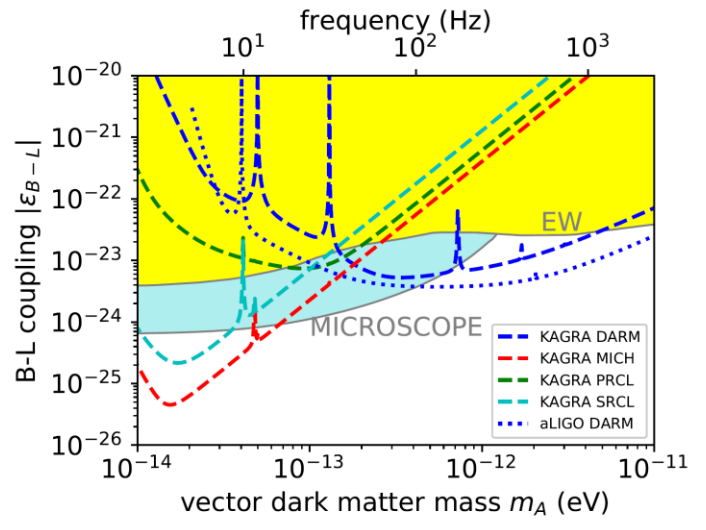
KAGRA beats aLIGO

You might guess KAGRA < aLIGO in the sensitivity to VDM…



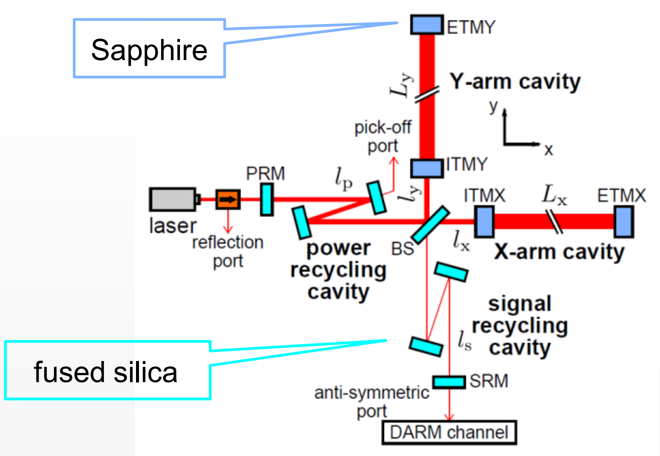


For B-L coupling, KAGRA goes beyond aLIGO

Michimura, TF, Morisaki, Nakatsuka and Obata PRD102, 102001(2020)

Auxiliary channels

All mirrors in aLIGO are fused silica, but KAGRA uses **sapphire** mirrors.



KAGRA measures

- DARM : $\delta(L_x - L_y)$
- MICH : $\delta(l_x - l_y)$
- SRCL : $\delta[(l_x + l_y)/2 + l_s]$

Michimura, TF, Morisaki, Nakatsuka and Obata PRD102, 102001(2020)

MICH & SRCL observe distance btw mirrors made of different material

→ **VDM acts differently**

B-L Charge

Different material ⟺ different charge for VDM

Acceleration : $\boldsymbol{a} = \boldsymbol{F}/M \propto Q_D/M$ charge/mass is important

B coupling : $Q_D = N_B$ ⟹ $\frac{N_B}{M} \approx \frac{N_B}{N_B m_n} = \frac{1}{m_n}$

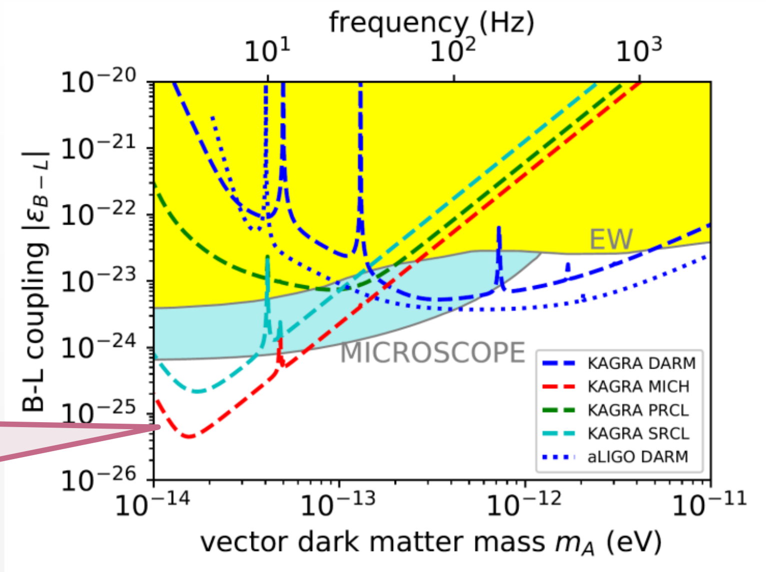
$B - L$ coupling : $Q_D = N_B - N_L$ ⟹ $\frac{N_B - N_L}{M} \approx \frac{N_B - N_L}{N_B} \frac{1}{m_n}$

Silica: 0.501, Sapphire: 0.51

VDM with B-L coupling differentiates mirror motion by 2%

KAGRA's sensitivity to VDM

Michimura, TF, Morisaki, Nakatsuka and Obata
PRD102, 102001(2020)



×10 improve the constraint

KAGRA will achieve the best sensitivity to VDM with B-L coupling by using the **auxiliary length channels**.

DM Summary

	Vector	Axion	WIMP
Image	**Electric wave with a mass**	**Birefringent media**	**Massive Particle**
Interaction	**B** or **B-L**	**Photon**	**Nuclei**
Search	?	?	**Particle collider** **Undergrond exp.**

N.b. other interactions are also possible

DM Summary

	Vector	Axion	WIMP
Image	**Electric wave with a mass**	**Birefringent media**	**Massive Particle**
Interaction	**B** or **B-L**	**Photon**	**Nuclei**
Search	**aLIGO DARM** **KAGRA Aux.**	**Add PD to KAGRA** **Data take in O4**	**Particle collider** **Undergrond exp.**

We are Hiring!

- **Two postdoc** positions from April 2021 for up to **4 years**
- Work on KAGRA and **DM search** at the University of **Tokyo**
- Deadline: **January 15**, 2021

https://www.s.u-tokyo.ac.jp/en/recruit/?id=1209

Thank You!

Message

GW detectors search for dark matter

- aLIGO O1 data ⟶ ×10 better bound on Vector DM
- Ongoing KAGRA projects probing Axion DM & Vector DM
- Huge parameter space will be searched by future GW detectors

Maybe we'll discover DM with GW interferometers!!